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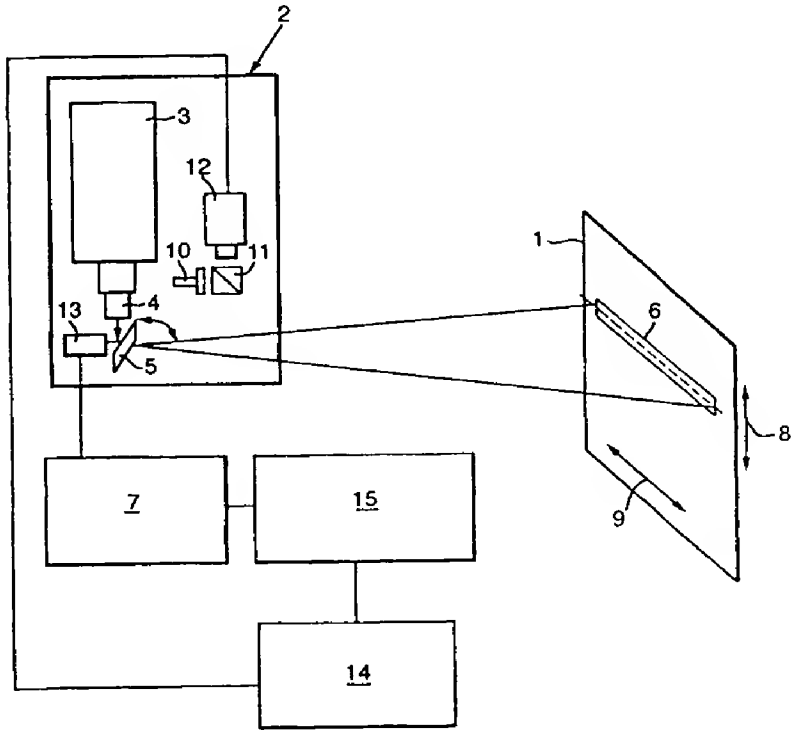
(54) Title: SPECKLE SHEARING–INTERFEROMETER FOR STRAIN MEASUREMENT

(57) Abstract

The signal to noise ratio in non–destructive testing or evaluation of a sample (1) by in phase stepped optical inspection systems such as the optical shearography system (2) using a shearing interferometer (11) involves production of correlated speckle images successively stepped in phase by illuminating with coherent radiation a sample (1) in an unstressed state, illuminating the sample (1) with coherent radiation, stressing it incrementally at predetermined stress increments, and generating and capturing correlated speckle images successively stepped in phase of the incrementally stressed sample (1) at the predetermined stress increments, using the phase stepped speckle images of the unstressed and incrementally stressed sample (1) to calculate the phase before and after stressing and differencing the images to extract the incremental phase change, inspecting the magnitude and sign of each incremental phase change.



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SPECKLE SHEARING-INTERFEROMETER FOR STRAIN MEASUREMENT

This invention relates to a method for increasing the signal to noise ratio in non destructive testing of a sample by a phase stepped optical inspection system which particularly, but not exclusively, is suitable for use with optical shearography employing a shearing interferometer.

A particular type of phase stepped optical inspection system for non destructive testing or evaluation of a sample is an optical shearography system using a shearing interferometer.

Such contemporary shearography systems measure the surface form of an object in a static position and after it has been subjected to a stressing force. Usually, the stress is administered by a pressure reduction chamber or by thermal loading. The two images that characterise the unstressed and stressed states are subsequently subtracted to yield an image that contours the stress-induced distortion. If the stressing force has been applied effectively, then sub-surface defects in the test object, such as disbonding between the skin and core materials of a composite panel, may be visualised in this image.

Unfortunately, there are several factors that limit the effectiveness of shearography for non-destructive testing (NDT) namely:

1. Shearography is based on speckle interferometry, which is inherently noisy.

2. If the stressing force is applied gradually over an extended period then the initial and final images may become de-correlated, due to environmental instability, and no result is produced.

3. The dynamic range of shearography is restricted, because of the limited spatial resolution of video based image acquisition.

4. Transient features, such as air currents, can mask the presence of defects.

A conventional technique known as phase stepping helps reduce image noise by eliminating stationary intensity patterns and enhancing image contrast. However, even if phase stepping is employed, the results are often too noisy and not sufficiently repeatable to be dependable for non-destructive testing or evaluation of safety critical structures.

There is thus a need for an improved method whereby the noise of shearography images is reduced and the repeatability of results is improved to an extent where shearography becomes viable for production non-destructive testing.

According to one aspect of the present invention there is provided a method for increasing the signal to noise ratio in non destructive testing of a sample by a phase stepped optical inspection system in which,

correlated speckle images successively stepped in phase are generated and captured of a sample to be tested or evaluated, by illuminating the sample, whilst in a static unstressed state, with coherent radiation,

the sample is illuminated with coherent radiation, stressed incrementally at predetermined stress increments, and correlated speckle images successively stepped in phase are generated of the incrementally stressed sample at the predetermined stress increments and captured,

the phase stepped speckle images of the unstressed sample and the phase stepped speckle images of the incrementally stressed sample are used to calculate the phase before and after stressing and differenced to extract the incremental phase change,

the magnitude and sign of each incremental phase change is inspected, and if the phase difference between successive measurements increases by more than π, 2π is subtracted from the measurement values, or if the phase

difference between successive measurements decreases by more than π, 2π is added to the measurement value and

the phase at each point in each speckle image is calculated with improved accuracy by summing the nearest neighbour phase differences in the image that are weighted by the square of their respective modulations, where the modulation is a measure of intensity variation with phase variation and the result of this calculation is normalised by dividing by the sum of the modulations.

Preferably the predetermined stress intervals employed are dependent on the material and structure of the sample.

Conveniently the phase differences are summed using a modulation filter in the form of a 3 x 3 convolution mask.

Advantageously the optical inspection system utilised is an optical shearography system incorporating a shearing interferometer, and the modulation is a measure of intensity variation with phase variation in the shearing interferometer.

For a better understanding of the present invention and to show how the same may be carried into effect, reference will now be made by way of example, to the accompanying single figure drawing Figure 1 which illustrates diagramatically a phase stepped optical inspection system in the form of a shearography system for utilising a method according to the present invention for increasing the signal to noise ratio in non destructive testing or evaluation of a sample employing the system.

The method of the present invention is intended to increase the signal to noise ratio in non destructive testing of a sample 1 conveniently an aircraft skin panel as illustrated in Figure 1 of the accompanying drawings by a phase stepped optical inspection system which conveniently is an optical shearography system using a shearing interferometer 2 as shown in Figure 1. Whilst the method of the present invention can be employed for reducing noise

in many coherent optical inspection systems, it will be described, for the sake of convenience, as utilised for improving the performance of a shearography system. Such a phase stepped optical shearography system utilises a laser 3 for providing a beam of coherent radiation for illuminating the sample 1. Conveniently the beam is produced via a line generator 4 and fed to a movable scanning mirror 5 from which the laser radiation is produced as a stripe 6 on the sample 1. The scanning mirror 5 is movable by means of a mirror driver amplifier 7 to scan in the direction 8 on the sample 1 and to move in the direction 9 on the sample 1 which is the direction of shear. The speckle pattern generated is observed by a piezo electric transducer 10 an interferometer 11 and a charge coupled device video camera 12. The laser 3, line generator 4, scanning mirror 5, transducer 10, interferometer 11, camera 12 and mirror drive 13 together make up the shearing interferometer 2. The video signal from the camera 12 is passed to a frame synchronising unit 14 and from thence to a triggered signal generator 15 and back via the mirror drive amplifier 7 and mirror drive 13 to control movement of the scanning mirror 5.

To improve the reliability of shearography systems, and reduce the noise floor, more statistically independent speckle data must be captured. Pressure stressing of the sample provides an ideal opportunity to capture this data, because the stressing force is highly controllable and is applied over an extended period. In principle it should be possible to integrate a series of incremental phase differences to yield the total phase difference, while incorporating more data and improving the signal-to-noise-ratio (SNR). However, to use this additional data effectively it has to be integrated in a coherent fashion so signatures from defects add constructively. There are two problems that prevent constructive integration of the data:

1. After phase information has been extracted from phase stepping of speckle images, the data is retrieved in a "wrapped" format due to the use of an inverse tangent operation in the calculation. This

means that the phase values are only known to module 2π (e.g. 7.5 is indistinguishable from 5.5π).

2. When the incremental phase differences are integrated, the intermediate phase terms cancel leaving only the difference between the first and last terms. consequently, the inherent SNR is not improved. This is illustrated more clearly by inspection of the following summation (equation 1) of component phase differences that is calculated over all of the images captured during the stressing process:

$$\phi = \sum_{i=0}^{n} [\varphi_i - \varphi_{i+1}] \qquad \ldots(1)$$

Where,

Φ - total phase change over the duration of the stressing process

φ_i - phase calculated from the ith sample

When this expression is expanded (equation 2), it is clear that the intermediate terms all cancel:

$$\Phi = (\varphi_n - \varphi_{n-1}) + (\varphi_{n-1} - \varphi_{n-2}) + \ldots (\varphi_i - \varphi_0) \qquad \ldots (2)$$

For effective data integration it is essential that the phase information is "unwrapped" prior to integration, otherwise large errors will be introduced and the final image will appear seriously fragmented. In practice, this is achieved by

inspecting the magnitude and sign of each phase difference. If the phase increases or decreases by more than π between successive measurements then a wrapping transition is deemed to have occurred and it is subsequently corrected (2π is added if the phase difference is sharply negative and 2π is subtracted if it is sharply positive).

Thus in the method of the present invention correlated speckle images successively stepped in phase are generated and captured using the system of Figure 1 for the sample 1 by illuminating the sample 1 whilst in a static unstressed state with coherent radiation from the laser 3. The sample 1 is then illuminated with coherent radiation from the laser 3, stressed incrementally at predetermined stress increments, and correlated speckle images successively stepped in phase are generated of the incrementally stressed sample at the predetermined stress increments and captured. The sample 1 is stressed in any convenient manner such as by means of thermal loading or by a pressure reduction chamber. The phase stepped speckle images of the unstressed sample and the phase stepped speckle images of the incrementally stressed sample are used to calculate the phase before and after stressing and differenced to extract the incremental phase change. Subsequently the magnitude and sign of each incremental phase change is inspected and if the phase difference between successive measurements increases by more than π, 2π is subtracted from the measurement value or if the phase difference between successive measurements decreases by more than π, 2π is added to the measurement value.

The phase at each point in each speckle image is then calculated with improved accuracy by summing the nearest neighbour phase differences in the image that are weighted by the square of their respective modulations where the modulation is a measure of intensity variation with phase variation, and the result of this calculation is normalised by dividing by the sum of the modulations. In the shearing system of Figure 1 the modulation is a measure of intensity variation with phase variation in the shearing interferometer 11.

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In effect to integrate the phase data, so that the intermediate terms do not cancel, it is necessary to decorrelate the speckle fields for each successive phase calculation. In practice, this is achieved by using regional information around each pixel to yield an improved estimate of the phase ϕ' at each point in the image. A modulation filter, conveniently implemented as a 3*3 convolution mask, is used to calculate the improved phase estimate. The modulation filter works by calculating a sum of nearest neighbour phase differences φ_1 that are weighted by the square of their respective modulations M_1^2, where the summation is over all of the mask elements i (equation 3).

$$\phi' = \Sigma\left(\varphi_i M_i^2\right) / \Sigma M_i^2 \qquad \ldots \quad (3)$$

The modulation M_i is a measure of how much the intensity of pixel i varies as the phase of one of the channels in the shearing interferometer is varied. Modulation is a reliable measure of the "performance" of each pixel and high values indicate that the phase estimate will probably be more accurate than lower values. The practical definition of M_i is given by equation 4:

$$M_i = \sqrt{\left\{2\left[I_2 - I_4\right] / \left[2I_3 - I_1 - I_5\right]\right\}} \qquad \ldots \quad (4)$$

Where I_1 to I_5 denote the intensities of the individual speckle images that are successively stepped in phase by $\pi / 2$ and then used to calculate the phase of each object state.

For the method of the invention to work effectively it is important that the data is sampled at the correct rate. If the phase is over-sampled as the

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pressure changes then the phase will not have changed much and only noise will be integrated. If the phase is under-sampled then wrapping transitions will be overlooked and errors will be introduced into the final image. In practice, for qualitative non destructive testing (NDT) it is usually acceptable if the largest defects contain unwrapping errors as they are still highly visible and this sampling rate often improves the detection rate of smaller less evident defects.

The correct sampling rate that is the predetermined stress intervals has to be determined empirically for each generic type of component, because it is a function of the material type and structural properties. Once this has been established the optimum sampling rate is achieved by capturing phase images at precise pressure increments. Ideally this should ensure that the pressure increments chosen lead to linear phase increments.

The method of the present invention is particularly suitable for increasing signal to noise ratio in coherent optical inspection systems such as the laser shearography system illustrated in Figure 1. The method of the invention has reduced tendencies to environmental instability which is a major factor that normally prevents exploitation of coherent optical systems. Additionally the method of the present invention has a larger dynamic range than usual testing methods, is tolerant to air currents and produces images of significantly higher signal to noise ratio.

CLAIMS

1. A method for increasing the signal to noise ratio in non destructive testing or evaluation of a sample by a phase stepped optical inspection system in which,

correlated speckle images successively stepped in phase are generated and captured of a sample to be tested, by illuminating the sample, whilst in a static unstressed state, with coherent radiation,

the sample is illuminated with coherent radiation, stressed incrementally at predetermined stress increments and correlated speckle images successively stepped in phase are generated of the incrementally stressed sample at the predetermined stress increments and captured,

the phase stepped speckle images of the unstressed sample and the phase stepped speckle images of the incrementally stressed sample are used to calculate the phase before and after stressing and differenced to extract the incremental phase change,

the magnitude and sign of each incremental phase change is inspected, and if the phase difference between successive measurements increases by more than π, 2π is subtracted from the measurement values, or if the phase difference between successive measurements decreased by more than π, 2π is added to the measurement value and

the phase at each point in each speckle image is calculated with improved accurancy by summing the nearest neighbour phase differences in the image that are weighted by the square of their respective modulations, where the modulation is a measure of intensity variation with phase variation, and the result of this calculation is normalised by dividing by the sum of the modulations.

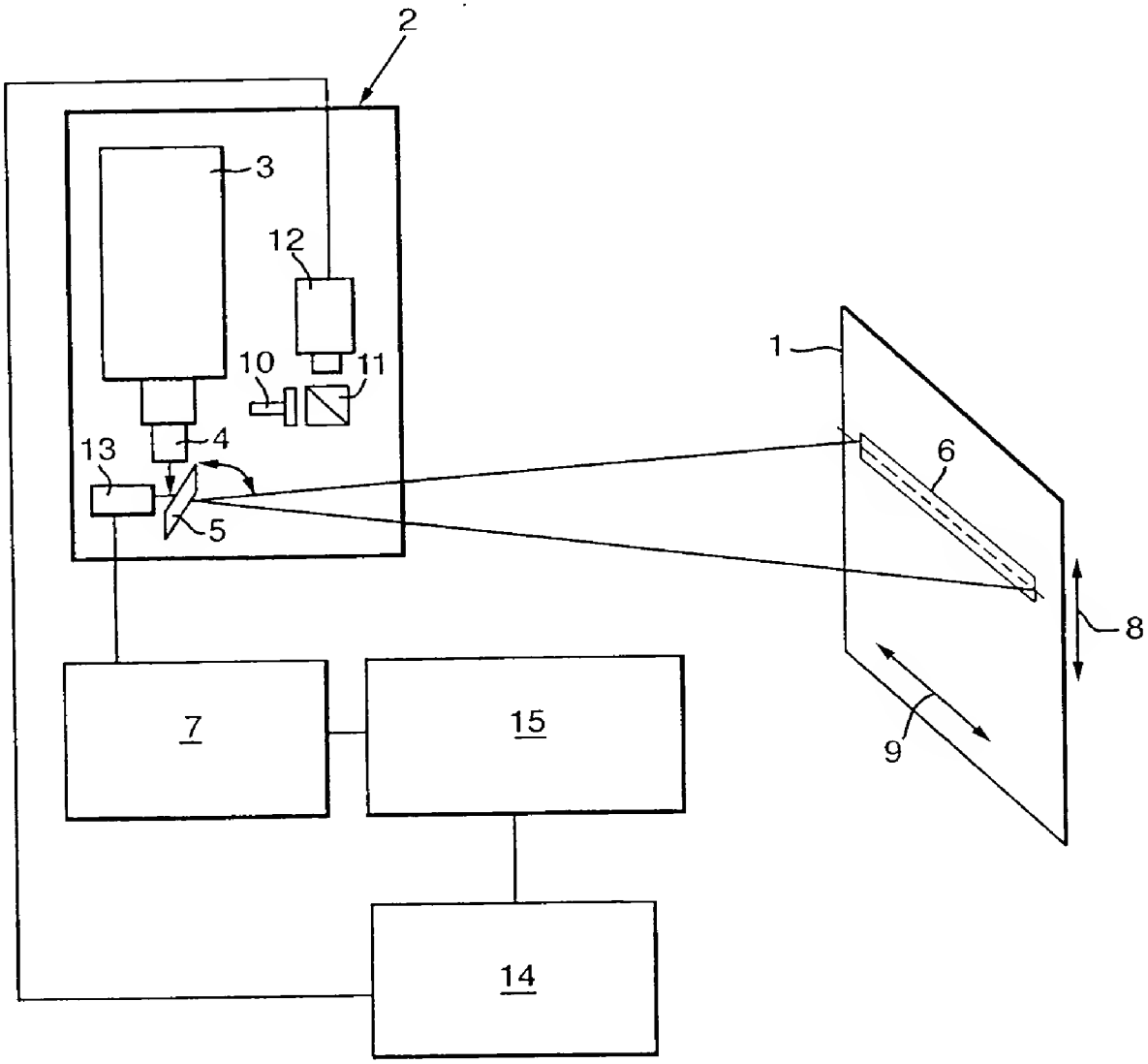
2. A method according to claim 1, in which the predetermined stress intervals employed are dependent on the material and structure of the sample.

3. A method according to claim 1 or claim 2, in which the phase differences are summed using a modulation filter in the form of a 3 x 3 convolution mask.

4. A method according to any one of claims 1 to 3, in which the optical inspection system utilised is an optical shearography system incorporating a shearing interferometer, and the modulation is a measure of intensity variation with phase variation in the shearing interferometer.

5. A method for reducing the signal to noise ratio in non-destructive testing of a sample by a phase stepped optical inspection system, substantially as hereinbefore described with reference to Figure 1 of the accompanying drawings.

Fig.1.



INTERNATIONAL SEARCH REPORT

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A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 G01B9/02 G01B11/16

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 G01B G01J G02B G06T

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	EP 0 875 744 A (BRITISH AEROSPACE) 4 November 1998 (1998-11-04) column 7, line 1 - line 22; figure 3	1,3,4
Y	WO 90 07751 A (EASTMAN KODAK CO) 12 July 1990 (1990-07-12) page 9, line 27 -page 11, line 5	1,3,4

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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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